

For existing machines, the following actions may delay failure:

- Clean the stator regularly if the machine is operating in an environment where chemicals are likely to be found.
- Ensure that the filters are effective.
- Use as benign a cleaning material as possible.
- Repair oil or water leaks as soon as possible.
- Ensure effective heater operation (where fitted, or consider retrofitting heaters), to prevent moisture condensation on the windings when the unit is cold.
- Ensure that old grease is expelled through grease relief plugholes when new lubricant is being added.
- Repair or replace an ineffective hydrogen dryer.

8.11 INADEQUATE END-WINDING SPACING

In large stators, space is left between adjacent coils in the end-windings to ensure that sufficient cooling air flows over them, to aid in limiting the winding temperature. In form-wound stators, particularly windings rated at 6 kV and above, adequate spacing is also needed to prevent partial discharge activity. If the spacing is too small, PD can occur, which may lead to ground and/or phase-to-phase faults. The problem does not happen on random-wound stators, and is unlikely to occur in high-pressure, hydrogen-cooled machines.

The partial discharge problem is most likely to occur in air-cooled machines rated at 6 kV or higher. It may also occur on stators rated at 3.3 kV and above that are using a thin ground-wall design. Although in a different location, the PD can also occur between circuit ring busses, coil connection insulation, or in the terminal leads if they are too closely spaced, especially if they are in different phases.

8.11.1 General Process

As was discussed in Section 1.4.4, partial discharges occur when a gas is subject to an excessive electric stress. Figure 8.9 shows a cross section of two adjacent coils or bars in the end-winding of a form-wound stator. The cross section can be thought of as three capacitors in series between the copper conductors: the capacitance of the A-phase groundwall, the capacitance of the air gap between the coil surfaces, and the capacitance of the B-phase groundwall. As a simplification, each of these capacitances can be calculated from a parallel plate model of a capacitor, in which the capacitance depends on the insulation thickness (or the distance between the coil surfaces in the case of the air gap) and the dielectric constant of the insulating material (see Equation 1.5). Using normal capacitive divider relationships from basic circuit theory, the percentage of voltage across the air gap can be calculated, knowing the thickness and the dielectric constants. From this, the electric stress is calculated (Equation 1.4). If the stress exceeds 3 kV/mm in an air-cooled machine at sea level (or a lower stress at high altitudes), the air breaks down, creating a partial discharge. Partial discharge most likely occurs when adjacent coils are connected to the phase terminals and in different phases, since the full rated voltage will drive the process.

Given sufficient time, the PD will erode a hole through the groundwall insulation. Since the discharges are usually occurring in air, ozone is created, which further accelerates the insulation deterioration process because the ozone creates an acid that also etches the insulation. The

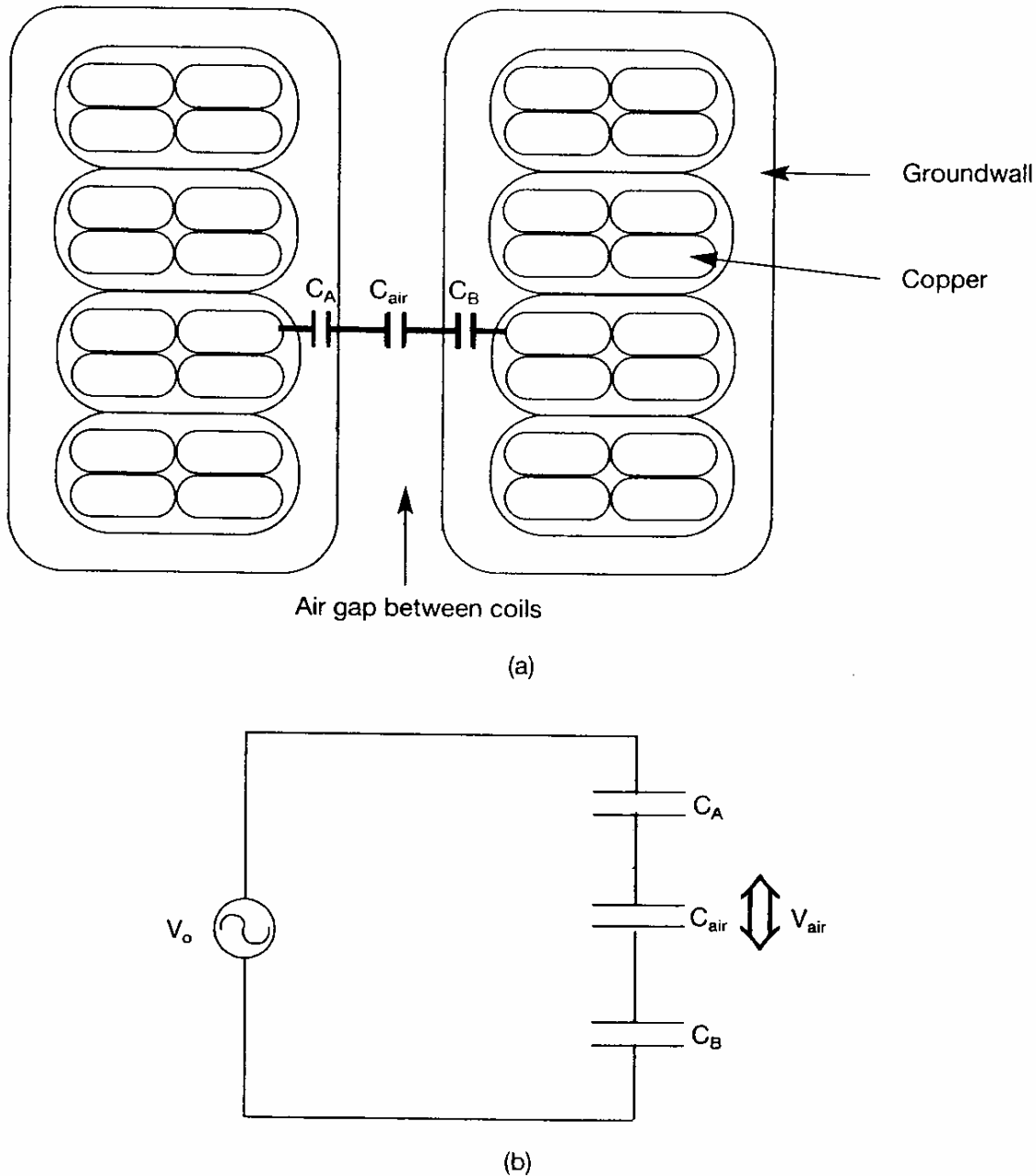


Figure 8.9. Cross section of two adjacent coils in the end-winding where PD will occur if the distance between the coils is too small.

ozone may also corrode heat exchangers and damage rubber gaskets. The time to failure is usually 5 years or more, since mica-based groundwall insulation is resistant to PD attack.

If the space between the coils is too small, typically less than 5 to 7 mm in a 13.8 kV winding with an average design stress of 2.5 kV/mm, PD will result if the full phase-to-phase voltage is across adjacent coils. PD is more likely at high altitudes, since the breakdown stress of air is lower in such locations. In addition, thin groundwall insulation designs increase the capacitance of the groundwall, reducing its capacitive impedance and applying more voltage across the gap. Consequently, such designs are more prone to this problem. High-pressure, hydrogen-cooled machines are less likely to have PD, since the breakdown strength of a high-pressure gas is many times higher than the strength at one atmosphere.

The problem will occur wherever adjacent coils (side-to-side or between the top and bottom layer of coils) are too close. This problem can also occur if high-voltage circuit ring busses are too close. An interesting variation has occurred in some hydrogenerators with Roebel bar windings and “end caps” used to insulate the connection between bars. The end cap insulation is often made by placing a polycarbonate (or similar material) mold over the connection and filling it with a thixotropic epoxy. The epoxy often contains fillers, but these are not especially PD resistant. If two adjacent end caps are insulating high-voltage connections in different phases, and the end caps are too close, PD will occur between them and damage the end caps. Since the mold and the epoxy are not resistant to PD, failure occurs in a period ranging from months to years. If the dielectric constant of the epoxy is too high, the capacitive reactance of the end cap will be low, increasing the stress across the air gap. Sometimes such PD only occurs when the generator is operating at high temperature, since the dielectric constant of the end caps is usually higher at high temperature.

8.11.2 Root Causes

Poor design and/or poor manufacture are the most likely cause of these problems:

- Insufficient space between coils for the altitude at which the machine is expected to operate. The purchaser may also be responsible if the OEM was not made aware of the intended location for the machine.
- Use of a thin groundwall design, without increasing the normal space between coils or making other provisions in the end-winding.
- Inconsistent coil shape after manufacturing. If one coil is longer than its adjacent coils, the longer coil must be closer to the adjacent coil than designed for, after the first bend in the end-winding.
- Poor installation of the coils in the slot. Even if the coils have identical shapes, if the first bend in a coil occurs farther out of the slot than the other coils, then it will close the space between the coils, after the first bend in the end-winding. An inadequate number of space blocks between adjacent coils may also make it harder for winders to keep consistent spacing between coils.
- Insufficient blocking or poor use of conformable packing may enable coils to bend in the end-winding, after high fault current or high motor starting current flow through the stator. This may reduce the distance between coils operating at greatly different voltages.
- Poor chemical control over the epoxy (in the coils or the end caps), which allows a high dielectric constant at operating temperature.

8.11.3 Symptoms

Usually, this mechanism is easy to spot in a visual inspection of the end-winding. Intense white powder (result of ozone attack) will occur between the coils (or end caps or circuit rings) connected to, or close to, the phase terminals (Figure 8.10). The most likely region for the white powder is where there are two adjacent phase-end coils in different phases. However, the powder can occur whenever any two adjacent coils have a sufficiently high potential difference. The white powder will not occur between neutral end coils, or where there is a



Figure 8.10. PD between adjacent coils in different phases results in white powder on the coil surfaces.

larger than average space between adjacent coils. The powder may assume shades of gray or brown in the presence of dust, debris, and oil.

On-line partial discharge tests are the most effective diagnostic means of finding the problem. (Off-line tests usually do not have sufficient voltage in the end-winding to initiate the PD.)

8.11.4 Remedies

To avoid this problem, testing and ensuring conformity to the specified distance between coils are needed at the time of stator manufacture. If the problem is discovered at an early stage of operation, very effective repairs are possible as discussed below.

- A good repair is to inject a conformable insulating material into the affected areas between the coils. Since a solid insulation has 100 times more electric strength than air, PD is prevented. Silicon rubber* or resin-filled felt pads are the most common materials used. For larger machines, resin-bonded glass fiber blocks wrapped with resin-filled felt are often used. Rigid epoxy-reinforced blocks or even mica flake are usually not as effective since air spaces often remain, which will give rise to very intense PD. Also, rigid materials may break away from the coil after load cycling, again creating

*There is some concern about the use of silicon rubber in a machine that has slip rings. The acetic acid released during cure by some types of silicon rubber can impair the operation of some types of slip rings. However, since a number of OEMs have been using silicon rubber for decades to secure coils in the slot, carbon brushes have been developed that are not affected by the acetic acid.